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Accelerator and detector physics at the Bern medical cyclotron and its beam transport line

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Abstract. The cyclotron laboratory for radioisotope production and multi-disciplinary research at the Bern University Hospital (Inselspital) is based on an 18-MeV proton accelerator, equipped with a specifically conceived 6-m long external beam line, ending in a separate bunker. This facility allows performing daily positron emission tomography (PET) radioisotope production and research activities running in parallel. Some of the latest developments on accelerator and detector physics are reported. They encompass novel detectors for beam monitoring and studies of low current beams.

Key words: beam monitoring • medical cyclotrons • particle accelerators • particle detectors

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The medical cyclotron in Bern and its beam transport line

Cyclotrons are used in medical applications mostly for radioisotope production for positron emission tomography (PET) and proton therapy. PET is a diagnostic technique requiring daily production of radiotracers. Most of the PET cyclotron centres produce ^{18}F for the synthesis of fluorodeoxyglucose (FDG).

The cyclotron laboratory in Bern is a part of the SWAN project aiming at the realization of a combined centre for radioisotope production, proton therapy and multi-disciplinary research [1]. The laboratory is equipped with an 18-MeV IBA high current cyclotron accelerating H^- ions, as shown in Fig. 1. There are eight proton out-ports. Four of them are equipped with ^{18}F liquid targets. One out-port is dedicated to the beam transport line (BTL) ending in a separate bunker. The cyclotron can produce 500 GBq of ^{18}F in about 80 min, corresponding to about 250 GBq of FDG.

The BTL allows carrying out multi-disciplinary research in parallel with daily radioisotope production [2]. The beam line consists of an upstream collimator, X-Y steering magnets, two quadrupole doublets, a neutron shutter, two beam viewers with Faraday cups for measuring the current and a beam dump. The beam dump can be replaced with a specific experimental apparatus. A schematic view of the cyclotron and the BTL is presented in Fig. 2.

The BTL was designed to perform research activities on accelerator and detector physics, radiation protection, radiation biophysics, radiochemistry and radiopharmacy. In the next sections, some selected recent developments on novel detectors

Fig. 1. The IBA 18-MeV cyclotron at the Bern cyclotron laboratory [1].

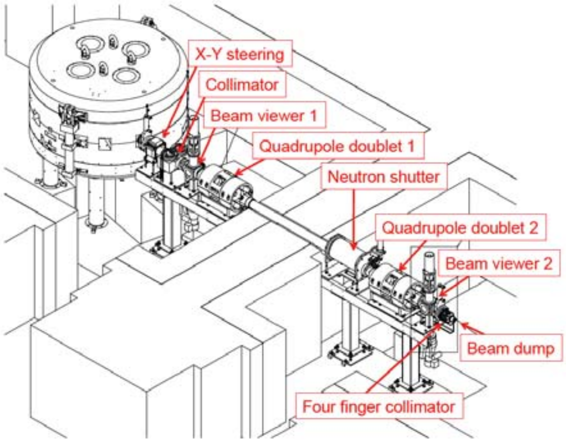

Fig. 2. Schematic view of the Bern cyclotron and its beam transport line.

for beam monitoring and low current beams are reported. A study of the radioactivity induced by protons extracted into air was recently performed and published [3].

Development of an innovative detector for beam monitoring

Beam monitoring is essential for any particle accelerator. The precise control of the beam is crucial in medical applications, radioisotope production and cancer radiotherapy in particular. Diagnostic devices are usually installed to obtain information for an optimal control during the whole irradiation process. Moreover, the accurate knowledge of the position, the intensity and the shape of the beam are needed for any experimental activity. Beam diagnostic instruments are usually conceived for specific applications [4], such as hadrontherapy, for which some sophisticated devices have been already developed. A general-purpose beam monitor suitable for both low (in the nanoampere range) and high (in the microampere range) currents would be highly beneficial. The first prototype of such a device has been recently conceived, constructed and successfully tested at the AEC-LHEP in Bern [5]. The working principle of the so-called universal beam monitor (UniBEaM) is reported in Fig. 3. A single

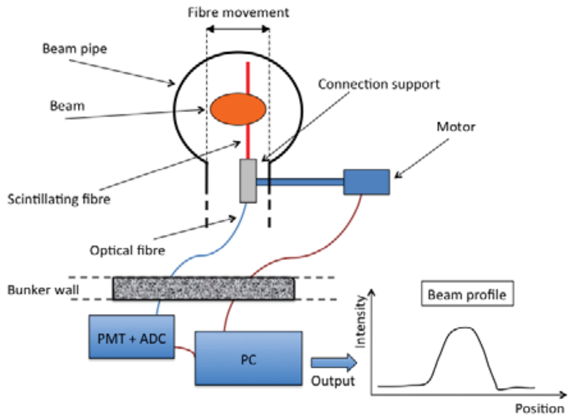

Fig. 3. Working principle and general scheme of a beam monitor detector based on a single scintillating fibre moving through a beam and coupled to an optical fibre.

silica-doped fibre is moved transversally through the beam and yielded light is sent through an optical fibre to a read-out device. In this way, the profile of the beam is measured and represented by the intensity as a function of the position. The sensing silica fibre is quite resistant to radiation and temperatures of up to 1300°C. As uncoated silica fibres are fragile and have a considerable attenuation (several dB/m), only about 10 cm of the sensing fibre is used. To transport the optical signal to the read-out device, the scintillating fibre is coupled to the optical fibre. The connection causes unavoidable light losses, which were estimated to be 20–50% by comparing the intensity of the light transmitted through the optical fibre with the one obtained with the fibre coupling. Although it is enough to measure the beam profile, the optimisation of the fibre coupling is under study. The sensing fibre is moved by a remote controlled motor. The read-out is provided by a photomultiplier or a photodiode connected via analogue-to-digital converter (ADC) to a computer. The detector is fully operated by means of the dedicated software developed at the AEC-LHEP.

The UniBEaM detector has been successfully tested in the cyclotron laboratory and already used for other experiments. The device installed on the BTL is shown in Fig. 4. The first measurement of a one-dimensional beam profile has been performed

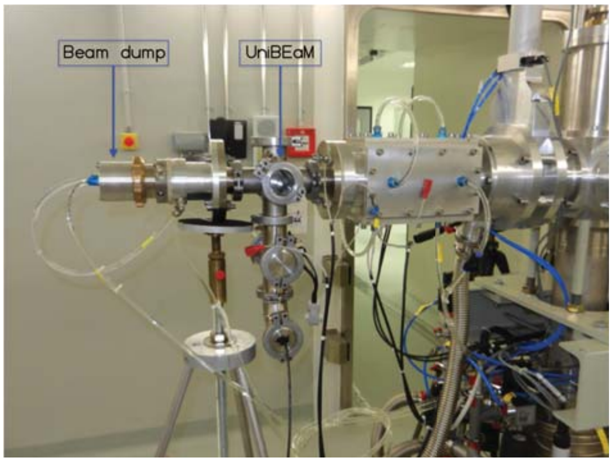

Fig. 4. The UniBEaM detector installed on the BTL in the Bern cyclotron laboratory.

using an Sb^{3+}-doped silica fibre. The obtained profile with the beam current of a few nanoampere is reported in Fig. 5.

The use of a single non-doped optical fibre for both producing and transporting scintillation light has been studied and tested with the 18-MeV cyclotron in Bern. This solution provides several benefits, such as no coupling between scintillating fibre and optical one with no light losses and a simple mechanics. The performed tests showed that the amount of impurities in a standard optical fibre is enough to cause scintillation using considerably high beam currents. The result of the beam profile measurement, performed with a beam current of 1 μA, is presented in Fig. 6. In this profile of the beam, a right-sided tail is observed. The tail can be due to stripping extraction in the cyclotron. In fact, not all of the H^- ions reach the stripper at the same turn. This results in a slightly higher energy of the protons coming from following turns. Such protons are seen as energy-shifted Gaussian beams, which can be extracted from the beam profile by fitting a double (multiple in general) Gaussian distribution. The fit allows dividing the beam into two components: the 18-MeV component and the energy-shifted component. In the case of measurement reported in Fig. 6, the full width at half maximum (FWHM)

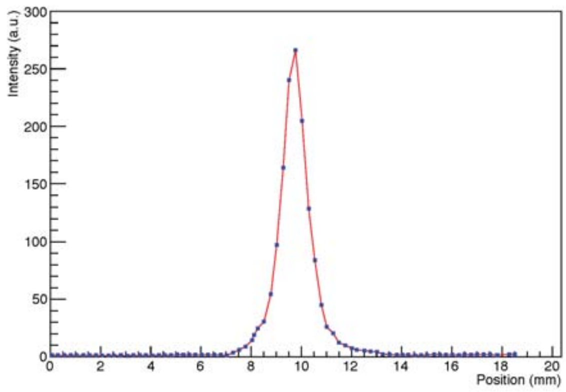

Fig. 5. Profile of the few nanoampere beam measured with an Sb^{3+}-doped silica fibre. Data points are connected by straight line segments for better readability.

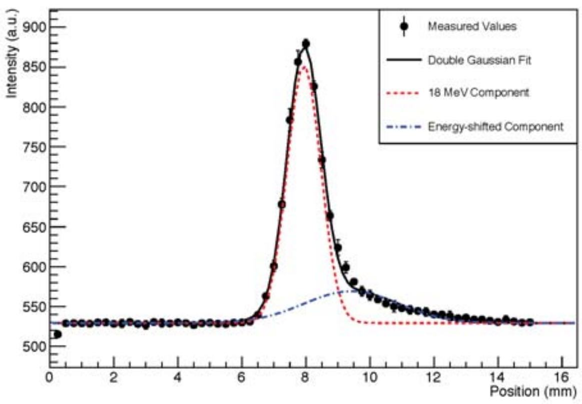

Fig. 6. Profile of the 1-μA beam measured with a single optical fibre. A double Gaussian fit is shown together with the two beam components. The 18-MeV component corresponds to the main beam of the cyclotron, whilst the energy-shifted component occurs due to H^- ions stripped at following turns.

of the former and the latter were found to be 1.25 ± 0.02 and 3.48 ± 0.23 mm, respectively. The occurrence and the location of the tail strongly depend on settings of quadrupole doublets. The energy-shifted components can be steered from left to right, and for some focalisations, they overlap with the main 18-MeV beam, as in the case of the profile reported in Fig. 5.

Low current beams with a medical cyclotron

Low current beams can be applied to many fields of multi-disciplinary research, as in the case of radiobiology. Cyclotrons for radioisotope production are conceived for high currents (~100 μA or more) and the lowest intensities guaranteed by manufacturers are usually of the order of 10 μA.

At the Bern cyclotron laboratory, a feasibility study aiming at low currents was performed. For precise measurements of beam current and stability, a Faraday cup adapted to the BTL and a sensitive electrometer were used. The Faraday cup installed on the BTL is presented in Fig. 7. The current of the proton beam was gradually decreased by changing current of the main coil and voltage of the radio frequency (RF) system, whilst keeping arc current of the ion source at the lowest possible value. Stable beams were observed in the picoampere range, reaching the minimum at 1.5 ± 0.5 pA.

Conclusions

The Bern cyclotron is fully operational for daily radioisotope production and research activities running in parallel. Some selected recent results on beam monitoring and low current beams are reported in this paper.

The UniBEaM detector represents a multi-purpose device of low complexity for beam diagnostics. It is suitable for large spectrum of beam currents from ~1 nA (typical for hadrontherapy) up to ~10 μA (radioisotope production).

Stable beams of low intensity, down to 1.5 pA, has been achieved with the Bern medical cyclotron. The obtained currents are seven orders of magnitude

Fig. 7. Faraday cup installed on the BTL.

lower than design range needed for radioisotope production. Such low currents are required by some multi-disciplinary activities usually not performed with this kind of accelerators as, for example, radiation biophysics.

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